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(54) **A VARIABLE SPEED DRIVE FOR THE SENSORLESS PWM CONTROL OF AN AC MOTOR BY EXPLOITING PWM-INDUCED ARTEFACTS**

DREHZAHLVARIABLER ANTRIEB FÜR SENSORLOSE PWM-STEUERUNG EINES WECHSELSTROMMOTORS UNTER AUSNUTZUNG VON PWM-INDUZIERTEN ARTEFAKTEN

ENTRAÎNEMENT À VITESSE VARIABLE POUR LE CONTRÔLE PWM SANS CAPTEUR D'UN MOTEUR À COURANT ALTERNATIF PAR L'EXPLOITATION D'ARTÉFACTS INDUITS PAR PWM

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- **WANG C ET AL: "A Novel Approach for Sensorless Control of PM Machines Down to Zero Speed Without Signal Injection or Special PWM Technique", IEEE TRANSACTIONS ON POWER ELECTRONICS, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, USA, vol. 19, no. 6, 30 November 2004 (2004-11-30), pages 1601-1607, XP011121751, ISSN: 0885-8993, DOI: 10.1109/TPEL.2004.836617**

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Description**Technical Field**

[0001] This disclosure generally pertains to the field of motor control. More precisely, it relates to Variable Speed Drives (VSDs), which are used to control the operation of Alternating Current (AC) electric motors. The focus is on VSDs that rely on Pulse-Width Modulation (PWM) to have continuous control over the speed of the controlled AC motor.

[0002] VSDs are typically used as industrial drives in factories, installations, HVAC systems and the like to control e.g. the position, speed and/or torque of an electric motor that is dedicated to a particular task, such as e.g. the operation of a fan or the hoisting of a load.

Background Art

[0003] In order to perform a closed-loop control of an AC motor, a VSD needs to have real-time information on the operating status of the AC motor. This information might for example be the instantaneous angular position and/or angular velocity of the motor's rotor.

[0004] The VSD may obtain this information from dedicated sensors, which are arranged on the motor and monitor the motor's operating status. However, fitting an electric motor with such sensors adds to the complexity and size of the whole drive assembly. The required sensors and sensor cabling also increase the price and reduce the reliability.

[0005] This is why so-called "sensorless" VSDs have become more and more common. In these sensorless VSDs, the motor's operating status is estimated on the basis of measurements of the motor's drive current. No additional external sensors are used. In order to improve the estimations, in particular when the motor operates at low velocity, it is a standard procedure to inject an external highfrequency probing signal into the motor's drive voltage.

[0006] The article "Adding virtual measurements by signal injection" by Pascal Combes et al., published in 2016 in the proceedings of the 2016 American Control Conference on pages 999 ff., conceptualizes and generalizes the signal injection technique for the sensorless control of electric motors at low speed.

[0007] Signal injection is an effective method, but it comes at a price: the ripple it creates may in practice yield unpleasant acoustic noise and excite unmodeled dynamics. In particular, in the very common situation where the electric motor is fed by a PWM inverter, the frequency of the injected probing signal may not be as high as desired so as not to interfere with the PWM (typically, it cannot exceed 500 Hz in an industrial drive with a 4 kHz-PWM frequency).

[0008] The article "A novel approach for sensorless control of PM machines down to zero speed without signal injection or special PWM technique" by C. Wang et al., IEEE Transactions on Power Electronics, Vol. 19, No. 6, Nov. 2004, pages 1601 ff., proposes to measure the phase current ripples induced by conventional PWM to derive the rotor position and speed of a PWM-controlled electric motor. However, this approach is based on the measurement of current derivatives, which requires specialized current sensors and is sensitive to noise.

Summary

[0009] In view of the above, it is an object of the present disclosure to provide a PWM-based variable speed drive with an improved sensorless AC motor control without signal injection.

[0010] According to the present invention, this object is achieved with a variable speed drive for the closed loop control of the operation of an AC electric motor based on a given control law, the variable speed drive comprising:

- an output terminal for delivering a controlled alternating drive voltage to the controlled AC electric motor;
- a solid-state power inverter for generating the drive voltage;
- a drive controller for controlling the generation of the drive voltage by the power inverter; and
- a drive current sensing device for measuring the instantaneous intensity of the drive current taken up by the controlled AC electric motor, and for providing the resulting measurements as a drive current intensity signal to the drive controller, wherein the drive controller includes:
 - a pulse-width modulation generator;
 - a control law module storing the given control law; and
 - a state variable estimation module for estimating the instantaneous value of at least one state variable of the controlled AC electric motor,

wherein the control law module is adapted to, based on the stored control law and state variable estimates provided by the estimation module, compute a target voltage signal and output the computed target voltage signal to the pulse-width modulation generator,

wherein the pulse-width modulation generator is adapted to:

- approximate the received target voltage signal with a pulse-width modulated inverter control signal;
- control the operation of the power inverter using the inverter control signal, thereby obtaining the drive voltage;
- compute, based on the deviation between the inverter control signal and the target voltage signal, a state variable estimation support signal; and
- output the computed state variable estimation support signal to the state variable estimation module, and

wherein the state variable estimation module is adapted to:

- estimate the instantaneous value of a state variable of the AC electric motor based on the received state variable estimation support signal and the drive current intensity signal provided by the drive current sensing device; and
- output the resulting state variable estimate to the control law module.

[0011] By modifying the PWM generator so that it computes an estimation support signal based on the PWM, and by providing this estimation support signal to the state variable estimator, the state variable estimator has supplementary information, which it can use to improve its state variable estimations.

[0012] Optionally, the variable speed drive according to the present disclosure can have the following features, separately or in combination one with the others:

- the pulse-width modulation generator is adapted to compute the state variable estimation support signal based on a pulse-width modulation inherent disturbance signal, which is obtained by subtracting the target voltage signal from the inverter control signal;
- the pulse-width modulation generator is adapted to compute the state variable estimation support signal by integrating the disturbance signal to obtain the primitive of the disturbance signal;
- the variable speed drive is adapted to rely on a single feedback to perform closed loop control of the AC electric motor, namely the drive current intensity signal provided by the drive current sensing device;
- the variable speed drive is adapted to control the operation of the AC electric motor without the injection of a dedicated probing signal into the drive voltage;
- the drive controller further includes an analog-to-digital converter for converting the drive current intensity signal into a digital signal prior to its input into the state variable estimation module;
- the state variable estimation module is adapted to estimate the instantaneous value of the rotor position of the electric motor based on the received state variable estimation support signal and the drive current intensity signal provided by the drive current sensing device;
- the pulse-width modulation generator is adapted to apply three-phase pulse-width modulation with single carrier to generate the inverter control signal;
- the pulse-width modulation generator is adapted to apply three-phase pulse-width modulation with interleaved carriers to generate the inverter control signal.

[0013] According to a further aspect, the present disclosure also relates to an electric drive assembly comprising a synchronous reluctance motor or a permanent-magnet synchronous motor and a variable speed drive as defined above for controlling the motor.

[0014] According to the present invention, the present disclosure also relates to a method of controlling, in a closed loop, the operation of an AC electric motor based on a given control law, the method comprising the following steps:

- a) measuring the instantaneous intensity of the drive current taken up by the controlled AC electric motor;
- b) estimating the instantaneous value of a state variable of the AC electric motor using the measured drive current intensity;
- c) computing, based on the given control law and the estimated state variable, a target voltage signal;
- d) approximating the computed target voltage signal with a pulse-width modulated inverting control signal;
- e) computing, based on the deviation between the inverting control signal and the target voltage signal, a state variable estimation support signal;
- f) generating, by voltage inversion, a controlled alternating drive voltage using the inverting control signal; and
- g) delivering the generated drive voltage to the controlled AC electric motor; wherein the state variable estimation according to step b) relies on the state variable estimation support signal computed in step e) as an additional input together with the drive current intensity measured in step a).

Brief Description of Drawings

[0015] Other features, details and advantages will be shown in the following detailed description and in the figures, in

which:

Fig. 1

[Fig. 1] is a block diagram of an electric drive assembly of the present disclosure, with a variable speed drive and an AC electric motor.

Fig. 2

[Fig. 2] is a block diagram illustrating the signal flow and processing in the electric drive assembly of Fig. 1.

Description of Embodiments

I. Exemplary setup of a variable speed drive according to the present disclosure

[0016] Figure 1 is a schematic diagram of an electric drive assembly 100 according to the present disclosure. The electric drive assembly 100 comprises a variable speed drive, or VSD, 200 and an AC electric motor 300.

[0017] The electric drive assembly 100 may be used in diverse industrial settings. For example, it may drive a fan of a heating, ventilation and air conditioning (HVAC) system. As another example, it may also be used to drive a water pump of a sewage installation. Many other industrial applications can be envisaged by the skilled person.

[0018] Preferably, the AC electric motor 300 is a synchronous motor, such as a permanent magnet synchronous motor, or PMSM, or a synchronous reluctance motor, or SynRM.

[0019] The purpose of the variable speed drive 200 is to control the proper operation of the electric motor 300. Thanks to the variable speed drive 200, the motor 300 can be operated at the right speed at the right time, depending on the application. The variable speed drive 200 may also allow to control the torque output of the electric motor 300 to its load.

[0020] The variable speed drive 200 controls the electric motor 300 in a closed loop. This means that the variable speed drive 200 constantly receives feedback on the instantaneous status of the motor 300 during the control of the motor. The variable speed drive 200 adjusts its control of the electric motor 300 based on a given control law. The specifics of the control law depend on the type of application of the electric motor 300.

[0021] With reference to figure 1, the variable speed drive 200 comprises an output terminal 210, a solid-state power inverter 220, a drive controller 230, and a drive current sensing device or current sensor 240.

[0022] The variable speed drive 200 is electrically connected to the electric motor 300 via its output terminal 210. The power output 210 delivers a controlled alternating drive voltage u_{pwm} to the AC electric motor 300. The drive voltage u_{pwm} is a modulated signal whose amplitude is determined by the DC voltage V_{bus} applied to the power inverter 220. The modulation frequency of the drive voltage u_{pwm} depends on the switching frequency of the power inverter 220. The modulated drive voltage u_{pwm} emulates an ideal sinusoidal drive voltage whose amplitude and frequency determine the operation of the electric motor 300.

[0023] The power inverter 220 generates the drive voltage u_{pwm} by chopping up a DC voltage with the help of solid-state switches T1, T2.

[0024] The skilled person will note that the diagram of figure 1 shows a single phase control. This is only for simplification. Typically, the electric motor 300 will be a three-phase motor. In this case, the power inverter 220 generates a drive voltage for each of the three phases of the motor.

[0025] The current sensor 240 of the VSD 200 measures the instantaneous intensity of the drive current taken up by the electric motor 300. The current sensor 240 provides its measurements as a drive current intensity signal i_s to the drive controller 230.

[0026] According to the present disclosure, the motor control by the VSD 200 is a so-called "sensorless" control. This means that the control feedback entirely relies on the current measurements provided by the current sensor 240. There are no external sensors mounted on the motor 300, such as shaft encoders and the like, to provide feedback to the VSD 200 on the motor status.

[0027] The drive controller 230 controls the generation of the drive voltage u_{pwm} by the power inverter 220. This is done on the basis of an inverter control signal M provided by the drive controller 230 to the power inverter 220.

[0028] The drive controller 230 may be implemented as a microcontroller or a field programmable gate array (FPGA).

[0029] According to the present disclosure, the drive controller 230 includes a pulse-width modulation, or PWM, generator 232, a control law module 234 storing the given control law, a state variable estimation module 236, and an analog to digital converter, or ADC, 238.

[0030] The control law module 234 is adapted to, based on the stored control law and state variable estimates z_0 to z_n provided by the estimation module 236, compute a target voltage signal u_s and output the computed target voltage signal u_s to the PWM generator 232.

[0031] The target voltage signal u_s represents the analog voltages that must be applied to the stator windings of the electric motor 300 to obtain the desired speed or torque from the motor 300.

[0032] Since the variable speed drive 200 relies on pulse-width modulation, the target voltage signal u_s is not directly applied to the electric motor 300. Rather, it is fed to the PWM generator 232 to be approximated by the pulse-width modulated inverter control signal M, which in turn is used to control the power inverter 220.

[0033] The pulse-width modulation generator 232 may apply three-phase pulse-width modulation with single carrier to generate the inverter control signal M (i.e. the approximation of the target voltage signal u_s).

[0034] Alternatively, the PWM generator may also apply three-phase pulse-width modulation with interleaved carriers to generate the inverter control signal M.

[0035] The PWM generator 232 may of course also use other PWM schemes to generate the inverter control signal M.

[0036] According to the present disclosure, the PWM generator 232 has the particularity that it computes, based on the deviation between the inverter control signal M and the target voltage signal u_s , a state variable estimation support signal s_1 , and outputs the computed state variable estimation support signal s_1 to the state variable estimation module 236.

[0037] The state variable estimation module or estimator 236 estimates the instantaneous value of one or more state variables of the AC electric motor 300 based on the drive current intensity signal i_s provided by the drive current sensor 240.

[0038] As shown in figures 1 and 2, the estimator 236 may estimate several state variables z_0 to z_n . These state variables may e.g. correspond to the rotor position of the electric motor, the angular velocity of the motor's rotor, etc.

[0039] According to the present disclosure, the estimator 236 also uses the estimation support signal s_1 to estimate the value of at least one of the state variables z_0 to z_n .

[0040] The estimator 236 provides the state variable estimates z_0 to z_n to the control law module 234. The control law module 234 uses these estimates in the stored control law in order to determine the target voltage signal u_s .

[0041] As shown in the figures, the drive controller 230 may also include an analog to digital converter 238. The purpose of the ADC 238 is to convert the analog current signal i_s provided by the current sensor 240 into a digital signal that can be processed by the estimator 236.

[0042] Figure 2 shows the signal flow between the different components of the electric drive assembly 100 of figure 1. The PWM generator 232 receives the target voltage signal u_s from the control law module 234. Using pulse-width modulation, it approximates the target voltage signal u_s by an inverter control signal M ($u, t/\varepsilon$). The inverter control signal M is fed to the power inverter 220. Based on this control signal M, the inverter 220 delivers a drive voltage u_{pwm} to the electric motor 300. With the current sensor 240, the currents in the motor's stator windings are measured and digitized in the ADC 238. The digitized current signal is then fed to the estimator 236. The estimator 236 also receives the estimation support signal s_1 ($u, t/\varepsilon$) from the PWM generator 232. The estimator 236 provides estimates of different motor state variables z_0 to z_n based on the received inputs.

[0043] An important aspect of the present disclosure is the enhanced PWM generator 232, which not only generates the inverter control signal M, but also the state variable estimation support signal s_1 . With the help of the estimation support signal s_1 , the estimation module 236 can extract supplementary information from the current signal i_s to improve the state variable estimations.

[0044] The PWM generator 232 computes the state variable estimation support signal s_1 based on a pulse-width modulation inherent disturbance signal s_0 . In fact, the present disclosure relies on the insight that the inverter control signal M generated by the PWM generator 232 can be modelled as a superposition of the target voltage signal u_s and a disturbance signal s_0 . Indeed, the inverter control signal M is a series of rectangular voltage pulses of varying widths, which on average, corresponds to the desired target voltage signal u_s . In other words, the inverter control signal M can be regarded as the desired target voltage signal u_s with an added voltage "ripple". This ripple or PWM disturbance in the voltage creates a disturbance in the stator flux of the motor 300, which in turn creates a disturbance in the measured current i_s .

[0045] The present disclosure takes advantage of this unintended side-effect of the pulse width modulation. The ripple/artefact induced by the pulse-width modulation in the measured currents is used in the state variable estimation. This improves the estimates and thus the control of the electric motor 300.

[0046] A measure of the pulse-width modulation disturbance signal s_0 (i.e. the ripple) can be obtained by subtracting the target voltage signal u_s from the inverter control signal M. The difference between the target voltage signal u_s and the inverter control signal M can then be integrated to obtain the primitive s_1 of the disturbance signal s_0 .

[0047] These calculations, namely the subtraction and the integration, are done by the PWM generator 232. As shown in the figures, the PWM generator 232 provides the result s_1 to the estimator 236.

[0048] It can be mathematically shown (see the remainder of the present disclosure) that the primitive s_1 is a useful input for the estimator 236 to determine the instantaneous value of a state variable of the electric motor 300, such as the rotor position θ .

[0049] The variable speed drive of the present disclosure is particularly useful for the control of synchronous electric motors at low speeds. By suitably using the excitation provided by the pulse-width modulation itself, the variable speed drive of the present disclosure has the same benefits as a conventional variable speed drive relying on an external excitation signal, without the drawbacks of increased acoustic noise and potential interference with the pulse width modulation.

[0050] In the variable speed drive of the present disclosure, standard pulse-width modulation does not need to be modified.

[0051] Also, the estimates by the estimation module 236 only require current measurements from standard current sensors. There is no need for current measurements at extremely precise instants, which is prone to measurement errors and very impractical in an industrial drive.

[0052] Furthermore, the variable speed drive of the present disclosure also does not require specialized sensors capable of measuring current derivatives, as in other known solutions.

[0053] The teachings of the present disclosure may also be applied to the control of other types of actuators. For example, one may think of controlling the operation of an electromagnet in a magnetic bearing, or of a solenoid valve of a hydraulic or pneumatic cylinder.

II. Mathematical derivation of exemplary estimators for sensorless electric motor control

[0054] Consider the control system modeled by the evolution equation

$$\begin{aligned}\dot{z} &= f(z) + g(z)u \\ y_a &= h(z)\end{aligned}\tag{1}$$

where z is the internal state vector of the system, u is the control input vector, and y_a is the measurement vector. In several practical applications (in particular electromechanical devices fed by a PWM inverter), the control input is not applied directly, but through a fast-periodic modulation which yields u only in the mean. The actual system is therefore

$$\dot{x} = f(x) + g(x)\mathcal{M}(u, t/\epsilon)$$

$$y = h(x)$$

where x is the state vector of the system disturbed by the modulator and y the corresponding measurement, $\epsilon > 0$ is a known small number, and $\mathcal{M}$ is 1-periodic and has mean u with respect to its second argument, i.e.,

$$\mathcal{M}(v, \sigma) = \mathcal{M}(v, \sigma + 1)$$

and

$$\int_0^1 \mathcal{M}(v, \sigma) d\sigma = v.$$

The system can clearly be written as

$$\dot{x} = f(x) + g(x)\left(u + s_0(u, t/\epsilon)\right)$$

$$y = h(x)$$

where s_0 defined by

$$s_0(v, \sigma) := \tilde{\mathcal{M}}(v, \sigma) - v$$

is 1-periodic and has zero mean with respect to its second argument, i.e., $s_0(v, \sigma) = s_0(v, \sigma + 1)$ and $\int_0^1 s_0(v, \sigma) d\sigma = 0$.

. In other words, we consider a generalized kind of signal injection, where the probing signal s_0 is generated by the modulation process itself; notice s_0 depends on u , which causes several difficulties.

[0055] Thanks to a mathematical analysis based on the theory of second-order averaging, it can be shown that the measured signal y may be written as

$$y(t) = y_a(t) + \epsilon y_v(t) s_1(u(t), t/\epsilon) + \mathcal{O}(\epsilon^2)$$

where s_1 , defined by $s_1(v, \sigma) := \int_0^\sigma s_0(v, s) ds - \int_0^1 \int_0^\sigma s_0(v, s) ds d\sigma$, is the zero-mean primitive of s_0 with u considered as a parameter; the "actual measurement" y_a and the "virtual measurement" $\overline{y_v s_1 s_1^T}$ can be interpreted as outputs of the "ideal" system without modulation (1), namely

$$y_a = h(z) \quad (2)$$

$$\overline{y_v s_1 s_1^T}(u) = h'(z) g(z) \overline{s_1 s_1^T}(u) \quad (3)$$

[0056] Notice the square matrix $\overline{s_1 s_1^T}(u) = \int_0^1 (s_1 s_1^T)(u, \sigma) d\sigma$ is in general invertible (see "Multiphase PWM" hereafter), so that we simply have $y_v = h'(z) g(z)$.

[0057] The overall purpose of the invention is to extract from the measured signal y estimates of y_a and y_v which can be used to control the system. All is then as if one would want to control the "ideal" system without modulation (1) with a feedback law relying not only on the "actual measurement" (2), but also on the "virtual measurement" (3). The problem is then simpler thanks to the supplementary information (3); in particular in the case of sensorless control electric motors at low velocity, this supplementary information gives access to the rotor position, hence is instrumental in the design of the control law. The invention consists mainly of two parts:

- 1) an enhanced modulator, generating not only the modulating signal $\mathcal{M}$, but also the zero-mean primitive s_1 of s_0
- 2) estimators $\hat{y}_a$ and $\hat{y}_v$ extracting not only y_a , but also y_v from the measured signal y , using the knowledge of s_1 .

[0058] A possible implementation for the estimators is

$$\hat{y}_a(t) := \frac{3}{2\epsilon} \int_{t-\epsilon}^t y(\tau) d\tau - \frac{1}{2\epsilon} \int_{t-2\epsilon}^{t-\epsilon} y(\tau) d\tau$$

$$\hat{y}_v(t) \overline{s_1 s_1^T}(u(t)) := \frac{1}{\epsilon^2} \int_{t-\epsilon}^t (y(\tau) - \hat{y}_a(\tau)) s_1(u(\tau), \tau/\epsilon) d\tau$$

related to the desired signals by

$$\hat{y}_a(t) = y_a(t) + \mathcal{O}(\epsilon^2)$$

$$\hat{y}_v(t) \overline{s_1 s_1^T}(u(t)) = y_v(t) \overline{s_1 s_1^T}(u(t)) + \mathcal{O}(\epsilon).$$

[0059] Notice these estimators are periodic low-pass filters with FIR (Finite Impulse response); many variants relying on different periodic low-pass FIR filters are possible.

III. Pulse-Width Modulation (PWM)

[0060] Generating analog physical power signals is extremely impractical, since a lot of power must be dissipated in the amplifier. Pulse Width Modulation (PWM) addresses the issue by using the transistors in saturation mode. Indeed, transistors are more efficient when they are used in saturation than when they are used in their linear range. The desired value is realized in average by adjusting the width of the pulses (hence the name of the technique).

[0061] The simplest way to realize a PWM modulator is to compare the analog signal u with a triangular carrier c oscillating between $-u_{max}$ and u_{max} as follows:

$$u_{PWM}(t) = \begin{cases} -u_{max} & \text{if } c(t) > u(t) \\ u_{max} & \text{if } c(t) < u(t) \end{cases} = u_{max} \text{sign}(u(t) - c(t))$$

where

$$c(t) = \begin{cases} 4u_{max} \left(\frac{t}{T} - k + \frac{1}{4} \right) & \text{if } \frac{t}{T} \in \left[k - \frac{1}{2}, k \right] \\ -4u_{max} \left(\frac{t}{T} - k - \frac{1}{4} \right) & \text{if } \frac{t}{T} \in \left[k, k + \frac{1}{2} \right] \end{cases}$$

[0062] This is the natural sampling PWM demonstrated in Figure 1 where the carrier is printed in blue, the analog signal is in red and the PWM signal is in yellow.

[0063] One of the disadvantages of the natural sampling PWM is that the pulses are not symmetrical. To address this issue, we can first sample the analog signal to obtain $u[k] = u(kT)$ and then apply the PWM modulation on the sampled signal as is demonstrated in Figure 2, where the analog signal is in purple and the sampled analog signal is in red. With this PWM scheme we can check that

$$\begin{aligned} \frac{1}{T} \int_{\left(k-\frac{1}{2}\right)T}^{\left(k+\frac{1}{2}\right)T} u_{PWM}(t) dt &= \frac{1}{T} \left(\int_{\left(k-\frac{1}{2}\right)T}^{\left(\frac{u[k]}{4u_{max}} + k - \frac{1}{4}\right)T} u_{max} dt - \int_{\left(\frac{u[k]}{4u_{max}} + k - \frac{1}{4}\right)T}^{\left(\frac{u[k]}{4u_{max}} + k + \frac{1}{4}\right)T} u_{max} dt + \int_{\left(\frac{u[k]}{4u_{max}} + k + \frac{1}{4}\right)T}^{\left(k+\frac{1}{2}\right)T} u_{max} dt \right) \\ &= \frac{u_{max}}{T} \left(\frac{u[k]}{4u_{max}} + \frac{1}{4} + 2 \frac{u[k]}{4u_{max}} - \frac{1}{2} + \frac{u[k]}{4u_{max}} + \frac{1}{4} \right) \\ &= u[k] \end{aligned}$$

[0064] The expression of u_{PWM} can be rewritten under the form $u_{PWM} = u + \tilde{u}$ with

$$\tilde{u} \left(\frac{t}{T}, u \right) = u_{max} \text{sign} \left(u - c \left(\frac{t}{T} \right) \right) - u,$$

which is a zero-mean fast-varying periodic signal with a dependence on the control.

IV. Poly-phase PWM

[0065] When controlling poly-phase electrical devices, $n > 1$ analog references must be modulated. In this case the

s_1 will be a vector with n lines and $\overline{s_1 s_1^T}$ is a $n \times n$ matrix.

[0066] Traditionally, to facilitate implementation, the n modulators use the same carrier. In this case, when two of the

references are equal, this control scheme leads to two equal components in s_1 , which means that $\overline{s_1 s_1^T}$ will not be invertible, which means that we do not obtain all the information in $h'(z)g(z)$. Besides, when two components are close

from one another $\overline{s_1 s_1^T}$ will be poorly conditioned, which complexifies the signal processing.

[0067] To get more information and improve the conditioning of $\overline{s_1 s_1^T}$, we can use a different carrier for each reference.

In this case, the components of are always independent. Consequently, the matrix $\overline{s_1 s_1^T}$, is always invertible and well-conditioned.

V. Application to sensorless control of an unsaturated synchronous reluctance motor (SynRM)

[0068] Using Clarke transformation matrices

$$C := \frac{2}{3} \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix}, \quad C^{-1} := \begin{pmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{pmatrix}$$

and the rotation

$$R(\theta) := \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$$

the model of the Synchronous Reluctant Motor (SynRM) is given by

$$\frac{d\phi_{SDQ}}{dt} = R(-\theta) C u_{Sabc} - R_s L^{-1} \phi_{SDQ} - J \omega \phi_{SDQ}$$

$$\frac{d\theta}{dt} = \omega$$

$$i_{Sabc} = C^{-1} R(\theta) L^{-1} \phi_{SDQ}$$

[0069] The state of this system is ϕ_{SDQ} , the vector of the stator flux in field-oriented DQ frame, and θ , the angular position of the rotor. The vector of stator voltages in physical abc frame, u_{Sabc} is the control input, while ω , the rotor speed, is a disturbance input, which must be obtained to achieve a proper control of the SynRM. When "sensorless" control is used the sole available measurement is the vector of stator currents in physical abc frame, i_{Sabc} . The

parameters of the model are the stator resistance R_s and the matrix of inductances $L := \begin{pmatrix} L_D & 0 \\ 0 & L_Q \end{pmatrix}$.

[0070] Since PWM is used, the voltage can be written $u_{Sabc}(t) = \bar{u}_{Sabc}(t) + \tilde{u}_{Sabc}(t/\epsilon, \bar{u}_{Sabc}(t))$.

[0071] Rewriting the system in the time scale $\sigma := t/\epsilon$, we obtain

$$\frac{d\phi_{SDQ}}{d\sigma} = \epsilon (R(-\theta) C \bar{u}_{Sabc} + R(-\theta) C \tilde{u}_{Sabc}(\sigma, \bar{u}_{Sabc}) - R_s L^{-1} \phi_{SDQ} - J \omega \phi_{SDQ})$$

$$\frac{d\theta}{d\sigma} = \epsilon \omega$$

$$i_{sabc} = C^{-1} \mathcal{R}(\theta) L^{-1} \phi_{SDQ}$$

[0072] Which is like the standard form of averaging. Applying the averaging procedure, we can show that the PWM disturbance in the voltages creates a disturbance in the stator flux, which becomes

$$\phi_{SDQ} = \bar{\phi}_{SDQ} + \epsilon \mathcal{R}(-\theta) C \tilde{U}_{sabc}(t/\epsilon, \bar{u}_{sabc}),$$

where $\tilde{U}_{sabc}$ is the primitive of $\tilde{u}_{sabc}$, with zero-mean over a PWM method. The flux disturbance in turn creates a disturbance in the measured currents which becomes

$$i_{sabc} = \bar{i}_{sabc} + \epsilon C^{-1} \underbrace{\mathcal{R}(\theta) L^{-1} \mathcal{R}(-\theta)}_{\mathcal{S}(\theta)} C \tilde{U}_{sabc}(t/\epsilon, \bar{u}_{sabc}) + O(\epsilon^2)$$

[0073] The undisturbed variables follow the original model

$$\frac{d\bar{\phi}_{SDQ}}{dt} = \mathcal{R}(-\theta) C \bar{u}_{s\alpha\beta} - R_s L^{-1} \bar{\phi}_{SDQ} - J \omega \bar{\phi}_{SDQ}$$

$$\frac{d\theta}{dt} = \omega$$

$$\bar{i}_{s\alpha\beta} = C^{-1} \mathcal{R}(\theta) L^{-1} \bar{\phi}_{SDQ}$$

[0074] Thanks to the proposed estimators, provided $\overline{\tilde{U}_{sabc} \tilde{U}_{sabc}^T}$ is invertible (see "Poly-phase PWM" above), we can recover $\bar{i}_{sabc}$ and

$$\mathcal{S}(\theta)$$

from i_{sabc} , which allows to run the original control law, which computes $\bar{u}_{s\alpha\beta}$ from $\bar{i}_{s\alpha\beta}$, and retrieve θ using

$$\mathcal{S}(\theta) = \mathcal{R}(\theta) L^{-1} \mathcal{R}(-\theta),$$

as can be done with HF injection, but without the need of an additional disturbance.

Claims

1. A variable speed drive (200) for the closed loop control of the operation of an AC electric motor (300) based on a given control law, the variable speed drive (200) comprising:

- an output terminal (210) for delivering a controlled alternating drive voltage (u_{pwm}) to the controlled AC electric motor (300);
- a solid-state power inverter (220) for generating the drive voltage (u_{pwm});

- a drive controller (230) for controlling the generation of the drive voltage by the power inverter (220); and
 - a drive current sensing device (240) for measuring the instantaneous intensity of the drive current taken up by the controlled AC electric motor (300), and for providing the resulting measurements as a drive current intensity signal (i_s) to the drive controller (230),

wherein the drive controller (230) includes:

- a pulse-width modulation generator (232);
- a control law module (234) storing the given control law; and
- a state variable estimation module (236) for estimating the instantaneous value of at least one state variable (z) of the controlled AC electric motor (300),

wherein the control law module (234) is adapted to, based on the stored control law and state variable estimates (z) provided by the estimation module (236), compute a target voltage signal (u_s) and output the computed target voltage signal to the pulse-width modulation generator (232),

wherein the pulse-width modulation generator (232) is adapted to:

- approximate the received target voltage signal (u_s) with a pulse-width modulated inverter control signal (M);
- control the operation of the power inverter (220) using the inverter control signal (M), thereby obtaining the drive voltage (u_{pwm}); **characterized in that** the pulse-width modulation generator (232) is further adapted to:

- compute, based on the deviation between the inverter control signal (M) and the target voltage signal (u_s), a state variable estimation support signal (s_1); and

- output the computed state variable estimation support signal (s_1) to the state variable estimation module (236), and that the state variable estimation module (236) is further adapted to:

- estimate the instantaneous value of a state variable (z) of the AC electric motor (300) based on the received state variable estimation support signal (s_1) and the drive current intensity signal (i_s) provided by the drive current sensing device (240); and

- output the resulting state variable estimate (z) to the control law module (234).

2. The variable speed drive (200) of claim 1, wherein the pulse-width modulation generator (232) is adapted to compute the state variable estimation support signal (s_1) based on a pulse-width modulation inherent disturbance signal, which is obtained by subtracting the target voltage signal (u_s) from the inverter control signal (M).

3. The variable speed drive (200) of claim 2, wherein the pulse-width modulation generator (232) is adapted to compute the state variable estimation support signal (s_1) by integrating the disturbance signal to obtain the primitive of the disturbance signal.

4. The variable speed drive (200) of any one of the previous claims, wherein the variable speed drive is adapted to rely on a single feedback to perform closed loop control of the AC electric motor (300), namely the drive current intensity signal (i_s) provided by the drive current sensing device.

5. The variable speed drive (200) of any one of the previous claims, wherein the variable speed drive is adapted to control the operation of the AC electric motor (300) without the injection of a dedicated probing signal into the drive voltage (u_{pwm}).

6. The variable speed drive (200) of any one of the previous claims, wherein the drive controller (230) further includes an analog-to-digital converter (238) for converting the drive current intensity signal (i_s) into a digital signal prior to its input into the state variable estimation module (236).

7. The variable speed drive (200) of any one of the previous claims, wherein the state variable estimation module (236) is adapted to estimate the instantaneous value of the rotor position of the electric motor (300) based on the received state variable estimation support signal (s_1) and the drive current intensity signal (i_s) provided by the drive current sensing device.

8. The variable speed drive (200) of any one of the previous claims, wherein the pulse-width modulation generator (232) is adapted to apply three-phase pulse-width modulation with single carrier to generate the inverter control

signal (M).

9. The variable speed drive (200) of any one of claims 1 to 7, wherein the pulse-width modulation generator (232) is adapted to apply three-phase pulse-width modulation with interleaved carriers to generate the inverter control signal (M).

10. An electric drive assembly (100) comprising a synchronous reluctance motor (300) and a variable speed drive (200) of any one of the previous claims for controlling the synchronous reluctance motor.

11. An electric drive assembly (100) comprising a permanent-magnet synchronous motor (300) and a variable speed drive (200) of any one of the previous claims 1-9 for controlling the permanent-magnet synchronous motor

12. A method of controlling, in a closed loop, the operation of an AC electric motor (300) based on a given control law, the method comprising the following steps:

- a) measuring the instantaneous intensity (i_s) of the drive current taken up by the controlled AC electric motor (300);
- b) estimating the instantaneous value of a state variable (z) of the AC electric motor (300) using the measured drive current intensity (i_s);
- c) computing, based on the given control law and the estimated state variable (z), a target voltage signal (u_s);
- d) approximating the computed target voltage signal (u_s) with a pulse-width modulated inverting control signal (M);

the method **characterized by** further comprising the following steps:

- e) computing, based on the deviation between the inverting control signal (M) and the target voltage signal (u_s), a state variable estimation support signal (s_1);
 - f) generating, by voltage inversion, a controlled alternating drive voltage (u_{pwm}) using the inverting control signal (M); and
 - g) delivering the generated drive voltage (u_{pwm}) to the controlled AC electric motor (300);
- wherein the state variable estimation according to step b) relies on the state variable estimation support signal (s_1) computed in step e) as an additional input together with the drive current intensity (i_s) measured in step a).

Patentansprüche

1. Frequenzumrichter (200) für die Regelung des Betriebs eines Wechselstrom-Elektromotors (300) basierend auf einem gegebenen Regelungsgesetz, wobei der Frequenzumrichter (200) umfasst:

- einen Ausgangsanschluss (210) zur Abgabe einer geregelten Antriebswechselspannung (U_{pwm}) an den geregelten Wechselstrom-Elektromotor (300);
- einen Festkörper-Wechselrichter (220) zum Generieren der Antriebsspannung (U_{pwm});
- eine Antriebsregeleinheit (230) zum Regeln des Generierens der Antriebsspannung durch den Wechselrichter (220); und
- eine Antriebsstrom-Sensorvorrichtung (240) zum Messen der momentanen Stromstärke des Antriebsstroms, der von dem geregelten Wechselstrom-Elektromotor (300) aufgenommen wird, und zum Bereitstellen der resultierenden Messwerte als Antriebsstromstärkensignal (i_s) für die Antriebsregeleinheit (230), wobei die Antriebsregeleinheit (230) beinhaltet:

- einen Pulsweitenmodulationsgenerator (232);
- ein Regelungsgesetzmodul (234), welches das gegebene Regelungsgesetz speichert; und
- ein Zustandsvariablen-Schätzmodul (236) zum Schätzen des momentanen Werts mindestens einer Zustandsvariablen (z) des geregelten Wechselstrom-Elektromotors (300),

wobei das Regelungsgesetzmodul (234) angepasst ist, um basierend auf dem gespeicherten Regelungsgesetz und Zustandsvariablen-Schätzungen (z), die von dem Schätzmodul (236) bereitgestellt werden, ein Zielspannungssignal (u_s) zu berechnen, und das berechnete Zielspannungssignal an den Pulsweitenmodulationsgenerator (232) auszugeben,

wobei der Pulsweitenmodulationsgenerator (232) angepasst ist zum:

- Annähern des empfangenen Zielspannungssignals (u_s) durch ein pulsbreitenmoduliertes Wechselrichterregelsignal (M);
- Regeln des Betriebs des Wechselrichters (220) durch Verwenden des Wechselrichterregelsignals (M), wodurch die Antriebsspannung (U_{pwm}) erhalten wird, **dadurch gekennzeichnet, dass** der Pulsweitenmodulationsgenerator (232) weiter angepasst ist zum:
- Berechnen, basierend auf der Abweichung zwischen dem Wechselrichterregelsignal (M) und dem Zielspannungssignal (u_s), eines Zustandsvariablen-schätzungsunterstützungssignals (s_1); und
- Ausgeben des berechneten Zustandsvariablen-schätzungsunterstützungssignals (s_1) an das Zustandsvariablen-Schätzmodul (236),

und dadurch, dass das Zustandsvariablen-Schätzmodul (236) weiter angepasst ist zum:

- Schätzen des momentanen Werts einer Zustandsvariablen (z) des Wechselstrom-Elektromotors (300) basierend auf dem empfangenen Zustandsvariablen-schätzungsunterstützungssignal (s_1) und dem Antriebsstromstärkensignal (i_s), das von der Antriebsstrom-Sensorvorrichtung (240) bereitgestellt wird, und
- Ausgeben der resultierenden Zustandsvariablen-schätzung (z) an das Regelungsgesetzmodul (234).

2. Frequenzumrichter (200) nach Anspruch 1, wobei der Pulsweitenmodulationsgenerator (232) angepasst ist, um das Zustandsvariablen-schätzungsunterstützungssignal (s_1) basierend auf einem der Pulsweitenmodulation eigenen Störsignal zu berechnen, das durch Subtrahieren des Zielspannungssignals (u_s) von dem Wechselrichterregelsignal (M) erhalten wird.
3. Frequenzumrichter (200) nach Anspruch 2, wobei der Pulsweitenmodulationsgenerator (232) angepasst ist, um das Zustandsvariablen-schätzungsunterstützungssignal (s_1) durch Integrieren des Störsignals zu berechnen, um die Stammfunktion des Störsignals zu erhalten.
4. Frequenzumrichter (200) nach einem der vorstehenden Ansprüche, wobei der Frequenzumrichter angepasst ist, um sich auf eine einzige Rückkopplung, nämlich dem Antriebsstromstärkensignal (i_s), das von der Antriebsstrom-Sensorvorrichtung bereitgestellt wird, zu stützen, um eine Regelung des Wechselstrom-Elektromotors (300) durchzuführen.
5. Frequenzumrichter (200) nach einem der vorstehenden Ansprüche, wobei der Frequenzumrichter angepasst ist, um den Betrieb des Wechselstrom-Elektromotors (300) ohne Einbringen eines dedizierten prüfenden Signals in die Antriebsspannung (U_{pwm}) zu regeln.
6. Frequenzumrichter (200) nach einem der vorstehenden Ansprüche, wobei die Antriebsregeleinheit (230) weiter einen Analog-Digital-Wandler (238) zum Umwandeln des Antriebsstromstärkensignals (i_s) in ein digitales Signal vor dessen Eingabe in das Zustandsvariablen-Schätzmodul (236) beinhaltet.
7. Frequenzumrichter (200) nach einem der vorstehenden Ansprüche, wobei das Zustandsvariablen-Schätzmodul (236) angepasst ist, um den momentanen Wert der Rotorposition des Elektromotors (300) basierend auf dem empfangenen Zustandsvariablen-schätzungsunterstützungssignal (s_1) und dem Antriebsstromstärkensignal (i_s), das von der Antriebsstrom-Sensorvorrichtung bereitgestellt wird, zu schätzen.
8. Frequenzumrichter (200) nach einem der vorstehenden Ansprüche, wobei der Pulsweitenmodulationsgenerator (232) angepasst ist, um Dreiphasen- Einzelträger-Pulsweitenmodulation anzuwenden, um das Wechselrichterregelsignal (M) zu generieren.
9. Frequenzumrichter (200) nach einem der Ansprüche 1 bis 7, wobei der Pulsweitenmodulationsgenerator (232) angepasst ist, um Dreiphasen-Pulsweitenmodulation mit verschachtelten Trägern anzuwenden, um das Wechselrichterregelsignal (M) zu generieren.
10. Elektrische Antriebsbaugruppe (100), umfassend einen Synchronreluktanzmotor (300) und einen Frequenzumrichter (200) nach einem der vorstehenden Ansprüche, zum Regeln des Synchronreluktanzmotors.
11. Elektrische Antriebsbaugruppe (100), umfassend einen Dauermagnet-Synchronmotor (300) und einen Frequenzumrichter (200) nach einem der vorstehenden Ansprüche 1-9 zum Regeln des Dauermagnet-Synchronmotors.

12. Verfahren zum Regeln, in einem geschlossenen Regelkreis, des Betriebs eines Wechselstrom-Elektromotors (300) basierend auf einem gegebenen Regelungsgesetz, wobei das Verfahren die folgenden Schritte umfasst:

- a) Messen der momentanen Stromstärke (i_s) des Antriebsstroms, der von dem geregelten Wechselstrom-Elektromotor (300) aufgenommen wird,
- b) Schätzen des momentanen Werts einer Zustandsvariablen (z) des Wechselstrom-Elektromotors (300) durch Verwenden der gemessenen Antriebsstromstärke (i_s);
- c) Berechnen, basierend auf dem gegebenen Regelungsgesetz und der geschätzten Zustandsvariablen (z), eines Zielspannungssignals (u_s);
- d) Annähern des berechneten Zielspannungssignals (u_s) durch ein pulsbreitenmoduliertes Wechselrichterregelsignal (M);

wobei das Verfahren **dadurch gekennzeichnet ist, dass** es weiter die folgenden Schritte umfasst:

- e) Berechnen, basierend auf der Abweichung zwischen dem Wechselrichterregelsignal (M) und dem Zielspannungssignal (u_s), eines Zustandsvariablen-schätzungsunterstützungssignals (s_1);
- f) Generieren durch Spannungswandlung einer geregelten Antriebswechselspannung (U_{pwm}) durch Verwenden des Wechselrichterregelsignals (M); und
- g) Abgeben der generierten Antriebsspannung (U_{pwm}) an den geregelten Wechselstrom-Elektromotor (300); wobei die Zustandsvariablen-schätzung gemäß Schritt b) auf dem Zustandsvariablen-schätzungsunterstützungssignal (s_1), das in Schritt e) berechnet wird, als zusätzliche Eingabe gemeinsam mit der Antriebsstromstärke (i_s), die in Schritt a) gemessen wird, aufbaut.

Revendications

1. Variateur de vitesse (200) pour la commande à boucle fermée du fonctionnement d'un moteur électrique à courant alternatif (300) sur la base d'une loi de commande donnée, le variateur de vitesse (200) comprenant :

- une borne de sortie (210) pour fournir une tension d'entraînement alternative commandée (u_{pwm}) au moteur électrique à courant alternatif commandé (300) ;
 - un onduleur de puissance à semi-conducteurs (220) pour générer la tension d'entraînement (u_{pwm}) ;
 - un dispositif de commande d'entraînement (230) pour commander la génération de la tension d'entraînement par l'onduleur de puissance (220) ; et
 - un dispositif de détection de courant d'entraînement (240) pour mesurer l'intensité instantanée du courant d'entraînement absorbée par le moteur électrique à courant alternatif commandé (300), et pour fournir les mesures résultantes comme un signal d'intensité de courant d'entraînement (i_s) au dispositif de commande d'entraînement (230),
- dans lequel le dispositif de commande d'entraînement (230) comporte :

- un générateur de modulation de largeur d'impulsion (232) ;
- un module de loi de commande (234) enregistrant la loi de commande donnée ; et
- un module d'estimation de variable d'état (236) pour estimer la valeur instantanée d'au moins une variable d'état (z) du moteur électrique à courant alternatif commandé (300),

dans lequel le module de loi de commande (234) est adapté pour, sur la base des estimations de la loi de commande enregistrée et de variable d'état (z) fournies par le module d'estimation (236), calculer un signal de tension cible (u_s) et délivrer le signal de tension cible calculée au générateur de modulation de largeur d'impulsion (232),

dans lequel le générateur de modulation de largeur d'impulsion (232) est adapté pour :

- approcher par approximation le signal de tension cible reçu (u_s) avec un signal de commande d'onduleur modulé en largeur d'impulsion (M) ;
- commander le fonctionnement de l'onduleur de puissance (220) en utilisant le signal de commande d'onduleur (M), obtenant ainsi la tension d'entraînement (u_{pwm}) ;

caractérisé en ce que le générateur de modulation de largeur d'impulsion (232) est en outre adapté pour :

- calculer, sur la base de la déviation entre le signal de commande d'onduleur (M) et le signal de tension cible (u_s), un signal de support d'estimation de variable d'état (s_1) ; et
- délivrer le signal de support d'estimation de variable d'état calculé (s_1) au module d'estimation de variable d'état (236), et que le module d'estimation de variable d'état (236) est en outre adapté pour :

- estimer la valeur instantanée d'une variable d'état (z) du moteur électrique à courant alternatif (300) sur la base du signal de support d'estimation de variable d'état reçu (s_1) et du signal d'intensité de courant d'entraînement (i_s) fourni par le dispositif de détection de courant d'entraînement (240) ; et
- délivrer l'estimation de variable d'état résultante (z) au module de loi de commande (234).

2. Variateur de vitesse (200) selon la revendication 1, dans lequel le générateur de modulation de largeur d'impulsion (232) est adapté pour calculer le signal de support d'estimation de variable d'état (s_1) sur la base d'un signal de perturbation inhérent à la modulation de largeur d'impulsion, qui est obtenu par soustraction du signal de tension cible (u_s) au signal de commande d'onduleur (M).

3. Variateur de vitesse (200) selon la revendication 2, dans lequel le générateur de modulation de largeur d'impulsion (232) est adapté pour calculer le signal de support d'estimation de variable d'état (s_1) par intégration du signal de perturbation pour obtenir la primitive du signal de perturbation.

4. Variateur de vitesse (200) selon l'une quelconque des revendications précédentes, dans lequel le variateur de vitesse est adapté pour reposer sur une seule rétroaction pour réaliser la commande à boucle fermée du moteur électrique à courant alternatif (300), à savoir le signal d'intensité de courant d'entraînement (i_s) fourni par le dispositif de détection de courant d'entraînement.

5. Variateur de vitesse (200) selon l'une quelconque des revendications précédentes, dans lequel le variateur de vitesse est adapté pour commander le fonctionnement du moteur électrique à courant alternatif (300) sans l'injection d'un signal de sondage dédié dans la tension d'entraînement (u_{pwm}).

6. Variateur de vitesse (200) selon l'une quelconque des revendications précédentes, dans lequel le dispositif de commande d'entraînement (230) comporte en outre un convertisseur analogique-numérique (238) pour convertir le signal d'intensité de courant d'entraînement (i_s) en un signal numérique avant son entrée dans le module d'estimation de variable d'état (236).

7. Variateur de vitesse (200) selon l'une quelconque des revendications précédentes, dans lequel le module d'estimation de variable d'état (236) est adapté pour estimer la valeur instantanée de la position de rotor du moteur électrique (300) sur la base du signal de support d'estimation de variable d'état reçu (s_1) et du signal d'intensité de courant d'entraînement (i_s) fourni par le dispositif de détection de courant d'entraînement.

8. Variateur de vitesse (200) selon l'une quelconque des revendications précédentes, dans lequel le générateur de modulation de largeur d'impulsion (232) est adapté pour appliquer un module de largeur d'impulsion triphasée avec une seule porteuse pour générer le signal de commande d'onduleur (M).

9. Variateur de vitesse (200) selon l'une quelconque des revendications 1 à 7, dans lequel le générateur de modulation de largeur d'impulsion (232) est adapté pour appliquer une modulation de largeur d'impulsion triphasée avec des porteuses entrelacées pour générer le signal de commande d'onduleur (M).

10. Ensemble d'entraînement électrique (100) comprenant un moteur à réluctance synchrone (300) et un variateur de vitesse (200) selon l'une quelconque des revendications précédentes pour commander le moteur à réluctance synchrone.

11. Ensemble d'entraînement électrique (100) comprenant un moteur synchrone à aimant permanent (300) et un variateur de vitesse (200) selon l'une quelconque des revendications précédentes 1 à 9 pour commander le moteur synchrone à aimant permanent.

12. Procédé de commande, dans une boucle fermée, du fonctionnement d'un moteur électrique à courant alternatif (300) sur la base d'une loi de commande donnée, le procédé comprenant les étapes suivantes :

- a) la mesure de l'intensité instantanée (i_s) du courant d'entraînement absorbé par le moteur électrique à courant

alternatif commandé (300) ;

b) l'estimation de la valeur instantanée d'une variable d'état (z) du moteur électrique à courant alternatif (300) en utilisant l'intensité de courant d'entraînement mesurée (i_s) ;

c) le calcul, sur la base de la loi de commande donnée et de la variable d'état estimée (z), d'un signal de tension cible (u_s) ;

d) l'approche par approximation du signal de tension cible calculé (u_s) avec un signal de commande d'ondulation modulé en largeur d'impulsion (M) ;

le procédé étant **caractérisé en ce qu'il** comprend en outre les étapes suivantes :

e) le calcul, sur la base de la déviation entre le signal de commande d'ondulation (M) et le signal de tension cible (u_s), d'un signal de support d'estimation de variable d'état (s_1) ;

f) la génération, par inversion de la tension, d'une tension d'entraînement alternative commandée (u_{pwm}) en utilisant le signal de commande d'ondulation (M) ; et

g) la délivrance de la tension d'entraînement générée (u_{pwm}) au moteur électrique à courant alternatif (300) ; dans lequel l'estimation de variable d'état selon l'étape b) repose sur le signal de support d'estimation de variable d'état (s_1) calculé à l'étape e) comme une entrée supplémentaire conjointement avec l'intensité de courant d'entraînement (i_s) mesurée à l'étape a).

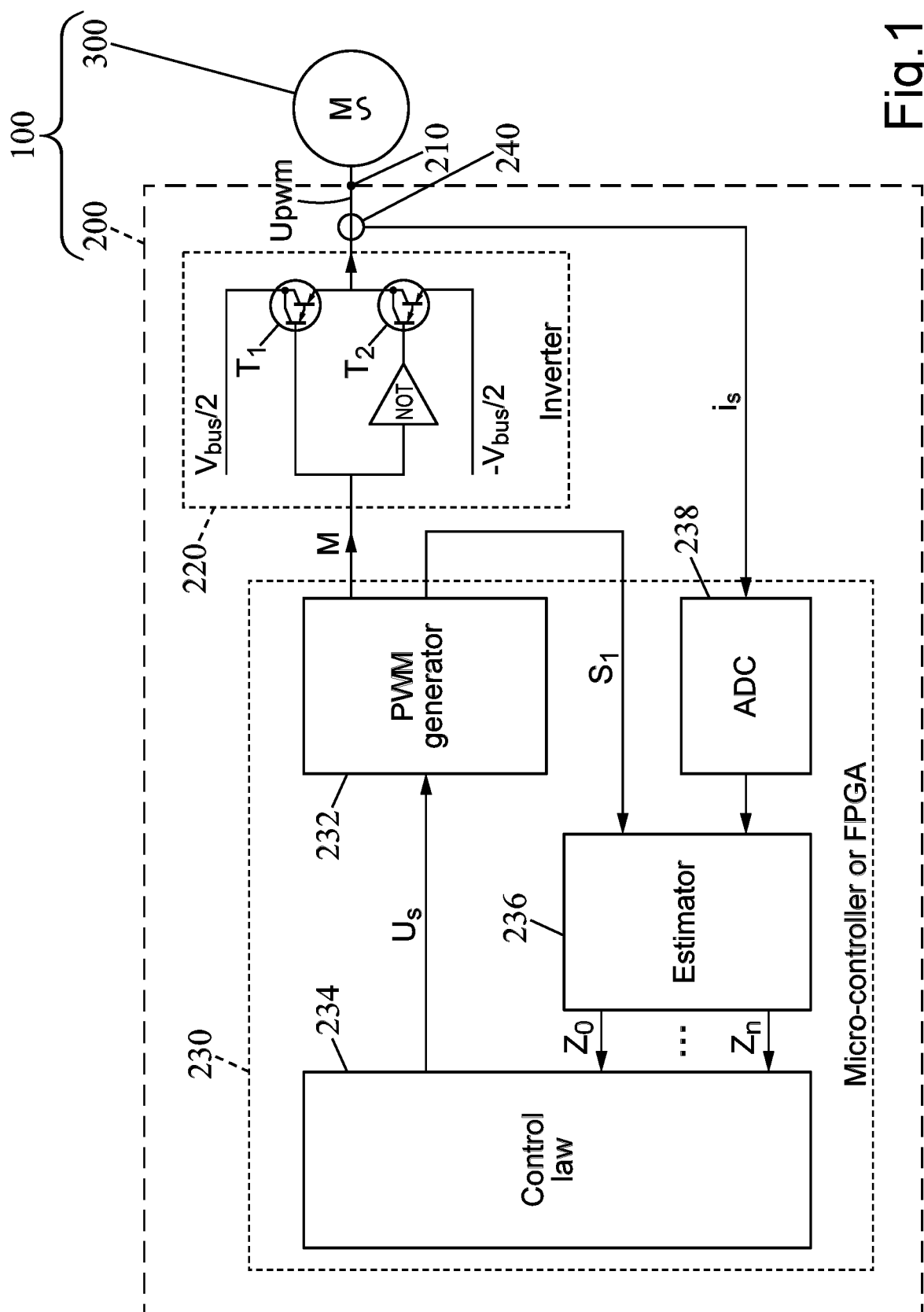


Fig.1

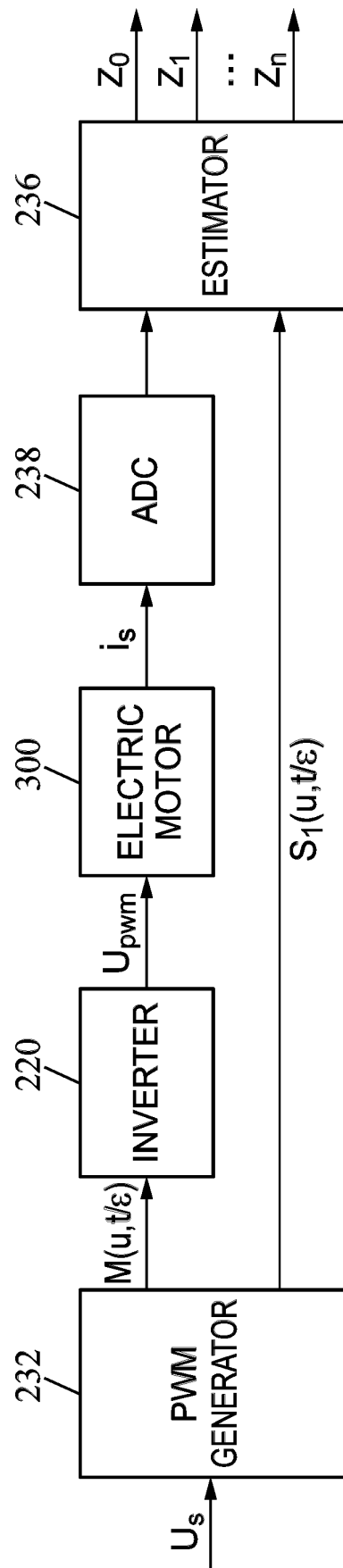


Fig. 2

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

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